

AU/ACSC/CARLSON, R/AY15

AIR COMMAND AND STAFF COLLEGE
AIR UNIVERSITY

**AIRCRAFT AND BASES POWERED BY COMPACT NUCLEAR
REACTORS: SOLUTIONS TO PROJECTING POWER IN
HIGHLY CONTESTED ENVIRONMENTS AND
FOSSIL FUEL DEPENDENCE**

by

Randall E. Carlson, Maj, USAF
PhD, astronomy
MS, physics

A Research Report Submitted to the Faculty

In Partial Fulfillment of the Program Completion Certificate Requirements

Advisors: Lt Col Michelle E. Ewy and Lt Col Paul P. Clemans

Maxwell Air Force Base, Alabama

May 2015

Disclaimer

The views expressed in this academic research paper are those of the author and do not reflect the official policy or position of the US government or the Department of Defense. In accordance with Air Force Instruction 51-303, it is not copyrighted, but is the property of the United States government.

TABLE OF CONTENTS

	<i>Page</i>
DISCLAIMERii
TABLE OF CONTENTS.....	iii
ABSTRACT.....	iv
Part 1: The Problem	1
The Current Situation	1
The Future.....	3
The Future War Environment	6
Part 2: The Solution	7
Nuclear Power is the Best Long-Term Solution	7
The US History of Nuclear Power Research	10
Problems with Most Nuclear Reactors Today	13
Nuclear Reactors for US Naval Vessels	15
Compact Nuclear Reactors for US Aircraft, Bases, and Spacecraft	16
Part 3: The Implementation Plan	20
Implementation Considerations	21
Political Hurdles.....	23
Step 1	25
Step 2	27
Step 3	27
Step 4	28
Conclusion	28
BIBLIOGRAPHY.....	33

ABSTRACT

The United States Department of Defense (DOD), especially the Air Force, currently requires huge amounts of energy to conduct daily operations, including the requirement to project power worldwide. As it prepares for operations in the future, specifically out to 2040 when the cost of fossil fuels will be even greater than today and the operational environment will be highly contested, the DOD must develop more sustainable methods of using energy than the current primary method of burning fossil fuels. Nuclear power is a sustainable solution existing today and is the most efficient energy-producing method. By leveraging decades of past research of its own and collaborating with the Navy, who has propelled vessels for sixty years using compact fission reactors, and the Department of Energy, the Air Force should develop its nuclear-power program based first on improved compact fission reactors and then on compact fusion reactors, which do not exist today but are being explored by industry. Compact reactors can power aircraft, increasing loiter time and power-projection range. They can also power expeditionary bases, decreasing the DOD's footprint and time needed to set up such bases. In short, the Air Force should project power in highly contested environments by 2040 with aircraft and bases powered by compact nuclear reactors.

Part 1

The Problem: Projecting Power without Fossil Fuels in Highly Contested Environments

The challenges faced by Ukrainian and European dependence on Russian energy supplies [put] a spotlight on the need for an expanded view of energy security ... as well as the importance of competitive energy markets.¹

– The US National Security Strategy, February 2015

...[M]odern warfare is evolving rapidly, leading to increasingly contested battlespace in the air, sea, and space domains—as well as cyberspace...²

– The US Department of Defense Quadrennial Defense Review, March 2014

The Current Situation: Increasing Energy Needs Mostly Obtained with Fossil Fuels

Throughout a relatively short history, humans have developed an increasing demand for energy to sustain a geopolitically and technologically evolving way of life. Presently in 2015, humans worldwide consume energy at an average rate of about 19 trillion joules per second, or watts, through an almost even split between energy for transportation and energy to power cities.³ To put this into some context, walking takes about 200 watts,⁴ a medium-sized car usually consumes 100 thousand watts,⁵ and in 2012 New York City needed 0.1 trillion watts on average.⁶ The United States consumes about 25 percent of the energy produced worldwide today and expects a continual high standard of living that can only come from increasing amounts of energy.⁷ The American dream, which results in wasteful energy consumption, is contagious, resulting in increasing energy-consumption trends around the globe in countries like China and India.⁸

Currently worldwide, most cities and modes of transportation rely on fossil fuels in the forms of oil or petroleum, coal, and natural gas. One can dissect the world's energy consumption as follows: 33 percent from oil, 25 percent from coal, 20 percent from natural gas, 15 percent from biomass and hydroelectric, seven percent from nuclear, and only one-half a percent from renewables like solar and wind.⁹ Hence, without fossil fuels, the world economy would come to

a crashing halt, and the American dream of a high standard of living would be impossible. As described in more detail later, fossil fuels will not last forever. Therefore, eventually humankind will be forced to transition to alternative forms of energy. In short, this paper is about transitioning to the nuclear alternative, especially for Department of Defense (DOD) power-projection and basing purposes.

As the United States' "largest single user of energy,"¹⁰ the DOD especially needs to explore transitioning away from fossil fuels. In 2013, the DOD spent about \$19 billion, or three percent of its budget, on fossil fuels, which it used for transportation fuel and for converting into electricity.¹¹ While three percent does not seem significant, this number will increase as the price of fossil fuels rises. The department is plagued with short-term thinking in regards to the transition path to fossil-fuel independence. For example, a July 2011 DOD study that looked at developing alternative fuels based on biomass by 2020 found that "the additional costs and potential adverse effects of creating a new DOD commodity class outweigh the potential benefits."¹² The study only looked at alternative fuels and did not look at other substitutes, such as nuclear energy. Unless it changes its short-term thinking approach and decides to be more proactive, the DOD will wait until the cost of fossil fuels increases to the point that other alternatives are cheaper, an unavoidable future situation. Time will tell, but by not proactively starting the transition before that point, the DOD likely will pay more in the long-term, since playing catchup could prove expensive and historically such transitions, such as the one from leaded to unleaded gasoline, take decades.¹³ The DOD currently does have a nuclear program for naval vessels. However, at this time, the DOD has no plans to expand this program beyond the sole naval use.

The Air Force is the largest consumer of energy inside the DOD.¹⁴ It requires huge amounts of energy to conduct daily operations, including the requirement to project power worldwide. Specifically, the Air Force uses fossil fuels to power its bases and to power and propel its aircraft. It almost completely gets its energy from fossil fuels. The Air Force spent roughly half of the \$19 billion that the DOD spent in 2013 on energy. The largest portion of the Air Force's energy budget goes to jet propellant 8 (JP-8), a petroleum-based fuel. In 2011, for example, the Air Force spent \$8.3 billion out of the \$9.7 billion energy bill on JP-8, or 86 percent.¹⁵ In some years, fuel prices rise more than predicted, creating an Air Force budget shortfall. For example, when this happened in 2012, the Air Force faced a \$1.3 billion deficit for fuel.¹⁶ This problem will get worse as energy markets become more volatile in the future. In short, as a huge user of energy, the Air Force must transition away from petroleum fuels in the short term and away from fossil fuels completely in the long term in order to mitigate the risk of rising and volatile fuel prices.

The Future: Decreased Levels of Fossil Fuels and Increased Competition for What's Left

Ever since the discovery of fire, humankind has consumed energy at an increasing rate with time. This rate of increase was slow before the industrial revolution and has been fast and increasing ever since. Specifically, humans have consumed as much energy in the last two decades as they did in all previous history.¹⁷ Today, humans consume energy at a rate of about 19 trillion watts, or about 2,700 watts per person. The US Energy Information Agency (EIA) projects that in 2040, humans will consume energy at a rate of about 27 trillion watts, or about 3,100 watts per person.¹⁸ At that rate, a person today driving a typical car would burn through an average gallon of regular unleaded gasoline in about 11 hours.¹⁹

The supply of fossil fuels is limited, and eventually humans will exhaust the supply. No one knows exactly when this will happen, but many energy experts make educated predictions. Michael Klare, author of multiple books on the geopolitics of energy, predicted in 2008 that this exhaustion would occur around the year 2100, noting that the world's major oil fields are already in production decline.²⁰ Since 2008, improvements in fossil fuel extraction techniques, such as fracking in the United States, have delayed the inevitable and probably pushed the depletion date past 2100.²¹ David Archibald, author of books and papers on climate science and a fellow at the Institute of World Politics, does not predict explicitly the date of complete exhaustion, but he does note that humans have consumed about half of the world's supply.²² Considering the rate of consumption continues to increase and assuming only half of the supply remains, sometime in the next century may be a good estimate. That may seem like a long time, especially to war planners, but it is not when considering the year 2100 is 85 years in the future, while the start of World War II was only about 75 years in the past. Finally, James Canton, chairperson of the Institute for Global Futures, predicts that humans will not wait for complete exhaustion. He stated, "The Stone Age did not end for lack of stone[,] ... [a]nd the Oil Age will end long before the world runs out of oil."²³

Until humans transition away from fossil fuels as their primary energy source, the average price of oil likely will continue to rise over the long term. Between 1990 and 2012, the worldwide price of a barrel of oil increased at an average rate of \$3.70 per year to a value of \$94.12 in 2012.²⁴ This historic trend has shown temporary periods of relaxation, such as the current one in 2015, which mostly is a result of higher US production due to fracking and inaction by the Organization of the Petroleum Exporting Countries (OPEC).²⁵ Assuming this relaxation does not change the historical trend of increasing oil prices with time and not

accounting for inflation, the US EIA predicts that the price of a barrel of oil will be \$106.99 in 2025, \$127.77 in 2035, and \$139.46 in 2040. However, indicative of a potentially increasing volatility, the price in 2040 could be as low as \$72.90 and as high as \$202.24.²⁶ In short, while the search for the earth's remaining fossil fuels spurs creativity, such as new fracking techniques, eventually even the most ingenious extraction techniques will not be enough for supply to keep up with demand, and humans will no longer be able to rely heavily on fossil fuel availability.

As the world's inhabitants continue to deplete the supply of fossil fuels, the competition for the remaining amounts will continue to become increasingly aggressive, and the importance of using alternative forms of energy will increase. David Archibald thinks humankind is currently in the "twilight of abundance" and predicts that the "rate of rise [of oil prices] will accelerate as countries become desperate."²⁷ The rising cost of fuel increases the cost of food and decreases the market for goods and services. Hence, not only is the competition for energy becoming increasingly aggressive, but so is the competition for food, goods, and services. In short, Archibald warns that unless immediate changes are made, such as becoming less reliant on fossil fuels, "life in the 21st century will be nasty, brutish, and short." He predicts hunger and death on a massive scale leading to uncontrollable criminal activity.²⁸ Therefore, the DOD must prepare for increased conflict around the globe due to resource competition and for an increased presence and power projection requirements due to the erosion of global security.

As if this future is not depressing enough, humankind must also deal with the problem that burning fossil fuels adds carbon dioxide to the atmosphere. The scientific and political communities are not in complete consensus that the additional atmospheric carbon dioxide is the primary cause for global warming, which humanity has observed in the short term and many predict for the long term.²⁹ The majority, which includes the US federal government, including

the DOD, state that global warming is happening and are starting to plan for it.³⁰ The DOD should care about climate change since it could change lines of transportation through the global commons and embolden countries like Russia. In fact, Navy Admiral Samuel Locklear thinks that climate change is the United States' biggest security threat in the Pacific region of the world.³¹ Climate change could also change the geopolitical landscape by decreasing the amount of useable land in certain parts of the world, creating conflicts. Despite these possible scenarios, the US greed for electric power and gasoline for transportation makes emission-reduction measures of fossil fuels mostly rhetoric instead of reality in the United States, and the DOD has a long way to go for fossil-fuel independence.

The Future War Environment: Highly Contested and Antiaccess / Area-Denial

As it prepares for operations in the future, the US DOD must develop more sustainable methods of producing and using energy than the current method of primarily burning fossil fuels. For example, by 2040, the cost of and the requirements for energy will be even greater than today and the operational environment will be highly contested, making power projection more difficult. In general, the United States should attempt to minimize the amount of fossil fuels it imports for economic and security reasons, as its dependence on foreign petroleum threatens future operations. In fact, the 2015 National Security Strategy contains an entire section on advancing our energy security.³²

By “highly contested,” the DOD is describing the operational environment of a potential AirSea Battle, doctrine that forms a critical part of its military strategy. The DOD recently renamed the doctrine the Joint Concept for Access and Maneuver in the Global Commons (JAM-GC).³³ Traditionally since at least the Persian Gulf War, the United States has used its technology, such as stealth for aircraft and Global Positioning System satellites, freely with little

resistance or denial of that technology from the enemy. In contrast, in a highly contested environment, the US military will receive strong resistance and attempts to deny technology in a way the DOD calls “antiaccess / area-denial” (A2/AD). Harry Foster at the US Air Force Center for Strategy and Technology states, “Defeating A2/AD is about keeping sensor and weapons density at range persistently without forward bases or aircraft carriers.”³⁴ In short, this paper proposes a solution of using nuclear power to address the two problems of needing to be able to project power at range in highly contested environments and needing to transition away from fossil fuels.

Part 2

The Solution: Aircraft and Bases Powered by Compact Nuclear Reactors

Therefore, we must promote diversification of energy fuels, sources, and routes ... while becoming a more efficient country that develops cleaner, alternative fuels and vehicles.”³⁵

– The US National Security Strategy, February 2015

...[T]he nuclear power generation upon which we depend is, due to its inhuman scale, too awkward, too expensive, too long in coming, and too scary. Because of time and money constraints, if we are to contain the threat of too much CO₂ in our fragile atmosphere, we must reduce the size of our nuclear plants to the scale and the ease of a backyard industry.³⁶

– Reese Palley in *The Answer: Why Only Inherently Safe, Mini Nuclear Power Plants Can Save Our World*, 2011

Nuclear Power is the Best Long-Term Solution over Other Alternatives

Currently, humankind’s energy consumption comes mostly from the burning of fossil fuels, but does consist of other sources, which include the burning of other forms of biomass, as well as hydroelectric, nuclear, solar, and wind power. However, humans use these other energy sources only 22 percent of the time worldwide today, because the price of using fossil fuels is mostly cheaper and the other sources have drawbacks.³⁷ As examples, renowned theoretical

physicist Michio Kaku states that the current cost of producing electricity by solar cells is several times the price of producing electricity by burning coal, and wind power has the drawback of being intermittent to when the wind blows.³⁸ However, as the price of oil increases and the technology to use the alternative forms improves and drives down cost, the other alternatives will become increasingly more attractive. For instance, Kaku estimates that in about fifteen years, the decreasing cost trend of solar cells will intersect the increasing cost trend of fossil fuels.³⁹

The DOD needs to transition away from fossil fuels and proactively overcome the hurdle of short-term thinking. Indicative of it starting to realize this, a 2014 “DOD Energy Policy” directive calls for improving “energy performance of our weapons, installations, and military forces”; “diversifying and expanding energy supplies and sources”; and for promoting “innovation for our equipment as well as education and training for our personnel, valuing energy as a mission-essential resource.”⁴⁰ Currently, with the exception of nuclear-powered naval vessels, the DOD sees the primary replacement of fossil fuels as alternative fuels based on other forms of biomass and not other energy sources. It currently considers nuclear energy for other than naval uses as having too many technical drawbacks and being too costly. Additionally, political hurdles, as described in Part 3, currently stand in the way of an extensive, DOD-wide nuclear program.

Besides the Pentagon, the White House also realizes the need to transition away from fossil fuels. The latest National Security Strategy devotes an entire section on advancing the American energy security. As other examples of small steps in the right direction, President Obama released in 2011 a “Federal Fleet Performance Memo,” mandating all new government vehicles purchased after 2015 to use alternative fuels,⁴¹ and stated in 2012 that nuclear energy is a clean energy that should be used to reduce the carbon dioxide pollution and climate change.⁴²

Finally, in 2015, President Obama unveiled the Solar Ready Vets Program, a collaborative program between the DOD and the Department of Energy (DOE), to train active-duty and unemployed veterans on solar panel installation.⁴³

Although diversifying energy sources is a good idea for humanity's unpredictable future, the best long-term solution is nuclear power for at least three reasons. First, nuclear power is more efficient than any other alternative. In other words, pound for pound, nuclear power, in the form of either nuclear fission or nuclear fusion, releases more energy than any other source. Fusion is the most efficient. As examples, fusion releases 10 million times more energy than gasoline, and, because water contains hydrogen, the energy content of an eight-ounce glass of water is approximately equal to a half a million barrels of petroleum.⁴⁴ In fact, fusion is nature's preferred method of energizing the universe, as revealed in the stars like our sun.

Second, unlike fossil fuels, fuels for nuclear energy are abundant and sustainable. As far as fuel for theoretical fusion reactors, hydrogen, deuterium, and lithium are plentiful on the earth and in the solar system. As far as fuel for existing and future fission reactors, uranium and plutonium are rare earth elements and probably could not provide a long-term solution by themselves. However, thorium, which is not fissile by itself but can be processed or transmuted into fissile uranium, is plentiful and a sustainable solution. While fossil fuels are running out and will last maybe one hundred years, the earth's supply of thorium could last for several millennia.⁴⁵ Additionally, using thorium in fission reactors instead of uranium or plutonium produces less nuclear waste.

Third, nuclear power is the best solution to minimizing and reversing climate change. Emphasizing this, Reese Palley, in his book *The Answer: Why Only Inherently Safe, Mini Nuclear Power Plants Can Save Our World*, declared, "all nonnuclear sources of electric power

either directly or indirectly produce carbon dioxide (CO₂) or directly or indirectly have warming consequences that are unacceptable.”⁴⁶ Economics and politics, not technology, prevent the United States from increasing its nuclear-power program, but, if the country takes certain steps starting now, this could change. The country will need these steps as the price of fossil fuels continues to increase and climate change increasingly becomes a security threat.

The US History of Nuclear Power Research, Especially inside the Department of Defense

Today, because of decades of research and development, proven nuclear technology includes nuclear fission power plants, fission and fusion nuclear weapons, fission nuclear-powered naval vessels, and radioactive generators for satellites, space probes, and even remote military outposts.⁴⁷ The International Atomic Energy Agency (IAEA) states that 443 nuclear power plants currently operate around the world, including 99 inside the United States, which is more than any other nation.⁴⁸ However, generally due to fears of nuclear accidents, which are rare, the United States and most countries worldwide mostly have not built a nuclear power plant since the 1980s and have only minimal plans to build new ones.⁴⁹ Led by the Obama administration and the DOE, the United States since 2011 has developed plans to construct five new plants.⁵⁰ Besides nuclear power plants, the most evident nuclear technology today exists in the US Navy, who currently has 82 nuclear-powered vessels comprising about 45% of the combat fleet.⁵¹

Throughout the years since the first nuclear detonation in 1945, American nuclear technology has improved greatly both inside and outside the DOD. Outside the DOD, first the US Atomic Energy Commission (AEC) and later the DOE, developed the nuclear power plant program, culminating today in the 99 old, but functional fission reactors throughout the United States.⁵² Additionally, first the AEC and later the National Aeronautics and Space

Administration (NASA) developed the radioisotope thermoelectric generator (RTG) for use in space and at remote military outposts.⁵³ Inside the DOD, after the Manhattan Project, the department took nuclear technology down four simultaneous exploratory paths: nuclear weapons, nuclear-powered bases, nuclear-powered naval vessels, and nuclear-powered aircraft.

First, the DOD, working with the AEC and later the DOE, improved nuclear weapon technology. Following this path triggered the very expensive and prolonged Cold War between the United States and the Soviet Union. This path for both the Americans and the Soviets consisted of improved fission bombs, fusion or thermonuclear bombs, and nuclear warheads on intercontinental ballistic missiles. Other countries over the years have taken similar paths, culminating in eight countries declaring they have nuclear weapons today.⁵⁴ Besides the 1945 nuclear detonations and various demonstrations throughout the years, all countries only have used and continue to use today these weapons for deterrence and political bargaining.

Second, from 1952 to 1979, the Army, working with the AEC, developed compact nuclear reactors and eventually used them operationally on Army bases. These compact nuclear power plants provided electricity for remote facilities, such as Fort Greely in Alaska and McMurdo Sound in Antarctica, for long periods without refueling. For example, the Army primarily powered Fort Greely with a single compact nuclear reactor from 1962 to 1972 with no accidents and minimal operational support. Despite the operational success of these reactors, the Army and AEC saw the program as research and development and expensive compared to traditional power plants burning fossil fuels. In order to fund the Vietnam War, the DOD greatly cut research and development, including the Army Nuclear Power Program.⁵⁵ Since 1979, this program has stayed dead. However, the Army demonstrated that compact nuclear reactors can power bases and are portable enough to set up quickly in remote locations like Antarctica.

Third, the DOD developed nuclear-powered naval vessels. The results of this technological path are apparent today. The DOD's report on "The United States Naval Nuclear Propulsion Program" states that, "since the USS NAUTILUS (SSN 571) first signaled 'underway on nuclear power' over 50 years ago in 1955, our nuclear-powered ships have demonstrated their superiority in defending the country—from the Cold War, to today's unconventional threats, to advances that will ensure the dominance of American seapower well into the future."⁵⁶ Over the years, the Navy has improved its operations, training, and radiological controls like shielding. Because of the program's demonstrated reliability, US nuclear-powered naval vessels today can take harbor worldwide in more than 150 ports in over 50 countries.⁵⁷

Fourth, between 1946 and 1961, first the US Army Air Forces and later the independent Air Force, collaborating with the AEC, tried to develop nuclear-powered aircraft.⁵⁸ Unfortunately, this Aircraft Nuclear Propulsion (ANP) program, despite spending over \$7 billion and being similar in some ways to the Navy program,⁵⁹ failed for at least three reasons. First, engineering adequate shielding for aircraft proved expensive, even though other engineers found cheaper solutions for naval vessels. The primary difference between the two types of vessels is the concern for weight, so engineering reactors for aircraft is more difficult. Second, national and DOD leadership frequently changed the emphasis and the objectives of the ANP program and did not provide sufficient and timely guidance. Two potential missions of ANP aircraft were air refueling and nuclear bomb delivery. Advances in air refueling technology and the development of the Intercontinental Ballistic Missile made these missions less relevant for the ANP program. Third, the public expressed concerns over the dangers of flying nuclear reactors. They expressed similar concerns regarding nuclear reactors in water, but people do not live in the water, so the perceived consequences of a nuclear accident by the Navy were less.

As a result of these reasons, President Kennedy cancelled the ANP program in 1961. However, before its cancellation, the Air Force successfully flew an operating nuclear reactor 47 times onboard a B-36 between 1955 and 1957. Although the reactor never powered or propelled the aircraft, the recurring demonstration proved the concept that a nuclear reactor can fit, operate, and be adequately shielded onboard an aircraft.⁶⁰ Since 1961, the Air Force has not had a nuclear power program. By leveraging decades of past research of its own and collaborating with the Navy and the DOE, the Air Force should reestablish its nuclear power program based first on improved compact fission reactors and then on compact fusion reactors. The DOD, leveraging proven results from the Army Nuclear Power Program, should resurrect the concept of powering its bases with compact nuclear reactors, especially as the price of fossil fuels continues to rise.

Problems with Most Nuclear Reactors Today

Most nuclear reactors operating around the world today consist of outdated technology, mostly as a result of unadaptable industrial inertia going all the way back to the American Manhattan Project of the 1940s. Nuclear reactors onboard naval vessels are the exception, while almost all nuclear reactors for power plants around the world follow this trend. Isotopes of only two heavy elements—uranium and plutonium—can fuel nuclear fission reactors. The early nuclear reactors for power plants were large, inefficient breeder reactors, which produced large amounts of radioactive waste.⁶¹ With few exceptions, almost all nuclear power plants around the world today have been operating for decades, using technology that is only slightly more efficient than the breeder reactor. For example, the average operational age of US nuclear power plants in 2015 is 36 years.⁶² As a result, most nuclear power plants today have three related drawbacks: they are unnecessarily large, they are not as safe as they could be, and they inefficiently produce large amounts of nuclear waste.

The first drawback of current nuclear power plants is they are unnecessarily large. Like many technologies, such as computers and cell phones, nuclear power plants started large. During this time in the 1950s, uranium and plutonium was expensive to produce and especially rare to find. Therefore, with the exception of compact nuclear reactors for the temporary and limited Army Nuclear Power Program, economy of scale thinking led to large, inefficient breeder reactors. While computers, cell phones, and nuclear reactors for naval vessels have all gotten smaller and more efficient with time, nuclear reactors for power plants have mostly stayed the same. Today's reactors almost entirely continue to use uranium and plutonium, even though processed thorium would be a better choice, as thorium is more abundant and produces less waste.⁶³ Nevertheless, the abundance and price of uranium, plutonium, and thorium today no longer dictate the need for large reactors. Smaller nuclear reactors take less time to build and are more portable, as the Army demonstrated. Although several nuclear countries have experimented with compact nuclear reactors and have even temporarily used them operationally, none of the 443 nuclear power plants operating worldwide today utilizes compact nuclear reactors. However, the US Navy currently uses such nuclear reactors to power naval vessels, and the Air Force could use them to power aircraft.

Second, nuclear power plants today are not as safe as they could be. To be clear, nuclear power plants are very safe and nuclear accidents are rare. Still, accidents, like the memorable ones at Chernobyl and Three Mile Island, have happened. Every nuclear reactor needs fissile fuel to burn and a cooling mechanism to dissipate the enormous amount of heat produced. Most of the current nuclear reactors, including those for naval vessels and for power plants around the world, use uranium for the former and water for the latter. This combination works under normal operations when the reactor's coolant pumps keep the water and dissipated heat circulating. In an

unplanned shutdown, like what happened when a tsunami hit the Japanese Fukushima Nuclear Power Plant in 2011, the core melts down if the reactor's coolant pumps stop working for long enough. The larger the reactor, the higher the probability of a core melting down during disrupted operations.⁶⁴ Therefore, smaller reactors are inherently safer.

Third, today's nuclear power plants inefficiently produce large amounts of nuclear waste. While nuclear energy has many positives, one negative is that splitting an atom produces nuclear waste, which is radioactive for up to millions of years, where the exact time depends on the isotope. In one year, a typical one-gigawatt reactor produces about 30 tons of nuclear waste.⁶⁵ Unlike other countries, the United States has yet to find an acceptable and permanent home for this waste and instead keeps it in temporary pools at the nuclear power plants.⁶⁶ Therefore, the nuclear waste problem as a whole is currently unmanageable and contributes to the poor perception the American public has regarding nuclear energy. In sum, the United States, especially the DOD, should transition away from large nuclear reactors and instead use compact nuclear reactors, which are safer and produce less nuclear waste.

Nuclear Reactors for US Naval Vessels: Compact and Safe with Manageable Waste

Fortunately, compact nuclear reactors exist today, as the US Navy has successfully demonstrated for sixty years. Today, as a result of successful technology development and acquisition paths, the US Navy operates 82 nuclear-powered vessels. The Navy uses their nuclear reactors onboard these vessels for propulsion and electricity. Because no step in the power production process requires air or oxygen, a submerged submarine is constrained by the amount of food the vessel can carry for the crew, not by the reactor. Like almost all current reactors, Navy reactors use uranium fission and pressurized water for cooling in a closed-loop

system. While the VIRGINIA-class reactor nominally lasts 33 years without refueling, the Navy is developing a new class of reactor that should have a 40-year operational lifetime.⁶⁷

The nuclear reactors used for naval vessels have at least three advantages over the nuclear reactors used for most nuclear power plants: they are compact, they are safe, and they produce an amount of nuclear waste that is manageable. First, the US naval nuclear propulsion plant is compact and can fit onboard a submarine. The energy-dense nature of nuclear power eliminates large tanks of propulsion fuel, permitting increased storage capacity for other purposes. Second, the plant is enclosed with thick shielding, ensuring the safety of the crew. In fact, a typical crewmember receives less radiation onboard a submerged nuclear submarine than someone working on land. Additionally, the uranium and radioactive waste are stored in high-integrity capsules that can withstand high-shock loading. Third, when a nuclear-power vessel is retired, the Navy properly stores the nuclear waste through standardized procedures and shielded containers. Today in the United States, the nuclear waste removed from nuclear-powered naval vessels is only about 0.05 percent of all existing nuclear waste.⁶⁸ In short, the US Navy has an outstanding nuclear program that has a 60-year history of success, safety, and efficiency.

Compact Nuclear Reactors for US Aircraft, Bases, and Spacecraft

Part 3 contains a more detailed implementation plan, but, in short, in order to solve the problems of projecting power in highly contested environments and fossil-fuel dependence, the US Air Force needs compact nuclear reactors for aircraft, and the DOD needs compact nuclear reactors for bases. Like current fission reactors onboard naval vessels, these reactors should be compact in order to be portable and safe and to produce a manageable amount of waste. The Air Force demonstrated it could fit, fly, and shield a compact nuclear reactor onboard a B-36 in the 1950s, but would need to engineer modern reactors for usage onboard modern aircraft. One of

the reasons the Air Force abandoned its nuclear reactor program in 1961 was the expense of developing lightweight shielding. Since 1961, nuclear reactor and shielding technologies have improved.⁶⁹ In sum, by collaborating with the Navy and the DOE, the Air Force should reactivate its own compact nuclear reactor program and then research, demonstrate, and operationalize nuclear-powered aircraft. Additionally, the DOD should incorporate nuclear-powered bases across the department.

Besides fossil-fuel independence, the DOD, especially the Air Force, could benefit from compact reactors in at least three ways: greatly increased power-projection capabilities for highly contested environments, portable power plants for expeditionary environments, and the elimination of certain logistics. The first benefit is greatly increased power-projection capabilities. Fuel currently constrains most aircraft missions. When an aircraft is low on fuel, it must land or be refueled in the air. With nuclear-powered aircraft, aircraft maintenance or a human factor replace aircraft fuel as the limiting factor. This could revolutionize civil and military air operations in many ways. The greatly increased power-projection capabilities include unlimited mission power-projection range and unlimited mission loiter time. As military examples, cargo and attack aircraft could benefit from increased range, while intelligence, surveillance, and reconnaissance (ISR) aircraft could benefit from increased loiter time. Therefore, nuclear-powered aircraft solve the A2/AD problem of keeping aircraft at range without forward bases or aircraft carriers. In 1955, General Electric developed the X-39 engine powered from a compact nuclear reactor. Although the X-39 never flew, General Electric showed in ground testing that a B-47 equipped with it could sustain a flight at 460 miles per hour for about 30,000 miles.⁷⁰ For comparison, today the B-2 can sustain a flight at 560 miles per hour for about 7,000 miles.⁷¹ Considering the relevant technologies have improved greatly in the last

60 years, a nuclear-powered aircraft today could most likely sustain or exceed the B-2's speed while greatly surpassing the range of the theoretical, nuclear-powered B-47. In short, nuclear power can provide endurance at high speeds for a long range, providing flexibility and allowing changes to missions while airborne.

Although the US Navy's current VIRGINIA-class reactor nominally lasts 33 years without refueling, one cannot assume that the exact same reactor would work as-is with minimal modifications for an aircraft. The Air Force, which is more concerned about vehicle weight than the Navy, would need to optimize a similar reactor for aircraft needs. Although nuclear-powered aircraft probably could not last 33 years without refueling, they could likely last weeks, according to Lt Col Brian Grelk, who researched nuclear-powered aircraft at Air Command and Staff College (ACSC) in 2009 and has a background in nuclear engineering.⁷² As technology improves, the time in between refueling will likely increase. One such potential technological improvement is the transition from compact fission reactors to compact fusion reactors, once researchers invent them. Assuming the reactor fuel will last weeks and that the nuclear reactor remains on while on the ground, engineers even could design a nuclear-powered aircraft to connect into and augment the base energy infrastructure.

Second, compact nuclear reactors could provide the DOD with portable power plants for expeditionary environments. Currently, whenever the US military first arrives on scene in an expeditionary environment and needs to stay in that location for a while, it first fulfills its power needs with portable but fossil-fuel-guzzling generators that require constant refueling. While these generators provide a quick, temporary solution currently, compact nuclear power plants could also provide that quick solution but in a more permanent and more self-sustaining manner. While a diesel generator can power a few buildings at most, a compact nuclear reactor, at

roughly the same size as the generator, could power an entire base or small city, as the Army demonstrated at Fort Greely and other locations. Replacing hundreds of generators with a single compact nuclear power plant decreases the footprint on the ground and to the environment and the time needed to set up and maintain such an energy infrastructure. Additionally, compact nuclear reactors could help the US military to perform humanitarian and nation-building missions, which US national leadership is asking the military to perform more and more, by more easily but temporarily providing electricity to areas in need.

Finally, compact nuclear reactors could eliminate certain military logistics. With all nuclear-powered aircraft and expeditionary bases, the DOD could minimize or eliminate the need for ground and air refueling. In fact, this concept could eliminate the need for US dependence on overseas airfields. The American B-2 currently conducts worldwide missions without ever landing overseas. However, it relies heavily on air-refueling aircraft to do so. With a fleet of nuclear-powered aircraft, the Air Force could expand that B-2 concept to all or most aircraft while not needing air refueling. Finally, besides just providing power, the DOD could use nuclear reactor and desalination technology together on a barge to convert seawater into potable water for human consumption and hydrogen fuel for transportation needs.⁷³ In sum, a solution to the problem of projecting power without fossil fuels in highly contested environments is using compact nuclear reactors to power aircraft and bases.

Although this paper concentrates on Air Force usages of compact nuclear reactors and presents usages for the entire DOD, obviously other organizations could benefit from the technology. Nuclear-powered aircraft capable of flying for weeks without landing could revolutionize both civil and military air operations. On the civilian side, clever entrepreneurs could come up with ideas such as airborne cruises that provide an aerial view of certain

interesting spots around the entire globe. Additionally, compact nuclear reactors paired with desalination technology on barges converting seawater into potable water and hydrogen fuel could revolutionize the geopolitics of these resources around the globe. Finally, compact nuclear reactors are also very attractive for propelling space vehicles, since the dense-energy output of nuclear power can get the spacecraft to far distances in shorter times than conventional space propulsion techniques. Over the years, many people and organizations, both inside and outside of the US government, have developed such proposals. Ted Taylor at General Atomics and physicist Freeman Dyson led a team from 1958 to 1963 to develop Project Orion, a plan for interplanetary and even interstellar travel using a series of controlled atomic bomb explosions.⁷⁴ More recently in the 1980s and then again in 2003 for the DOE, the Lawrence Livermore National Laboratory proposed a Vehicle for Interplanetary Space Transport Applications (VISTA) using inertial confinement fusion technology.⁷⁵ In short, the applications of compact nuclear reactor technology, both inside and outside the DOD, are numerous.

Part 3

The Implementation Plan: Expanding the DOD's Compact Nuclear Reactor Program

Nuclear power is the obvious solution. But not the currently dominant technology, uranium-burning light-water reactors... Thankfully, there is another route to exploiting nuclear power that is not only safer but also cheaper—thorium-burning molten-salt reactors.⁷⁶

– David Archibald in *Twilight of Abundance: Why Life in the 21st Century Will Be Nasty, Brutish, and Short*, 2014

Lockheed Martin Corp said...it had made a technological breakthrough in developing a power source based on nuclear fusion, and the first reactors, small enough to fit on the back of a truck, could be ready for use in a decade.⁷⁷

– Andrea Shalal, Reuters, 15 October 2014

Implementation Considerations

By leveraging decades of past research of its own and collaborating with the Navy and the DOE, both who currently have successful nuclear power programs, the Air Force should develop its nuclear power program in order to produce nuclear-powered aircraft. Additionally, the DOD should expand its nuclear power program in order to produce nuclear-powered bases worldwide. These programs are essential for transitioning away from fossil fuels. The transition from fossil fuels to nuclear energy will take decades but should start immediately. In the short term, changing the energy infrastructures of the DOD and the country to ones based more on nuclear reactors and less on fossil fuels is expensive. However, in the long term, it could save money as the cost of a barrel of oil continues to rise. The Air Force has a lot to gain from nuclear energy. Besides being the DOD service with the largest energy needs, it also has the largest diversity of assets—bases, airplanes, and satellites—that could benefit from nuclear power. The Navy has already embraced nuclear reactor technology, and the Air Force needs to as well. As the Army already demonstrated the technology and operational concept, the DOD needs to reinstate powering bases with compact nuclear reactors.

Besides collaborating with the DOE, the DOD should team up with industry. For example, Lockheed Martin is working currently on developing a compact nuclear fusion reactor. The Air Force has a long history of developing and fielding technology, such as stealth, with Lockheed Martin. However, because federal acquisition regulations require competition under normal circumstances and competition usually spurs innovation, the DOD cannot just work with Lockheed Martin. In addition, many people and organizations, such as Lawrence Livermore National Laboratory for spacecraft applications, continue to propose ideas, but independent

experts need to determine if these ideas are realistic for the long-term needs of the United States, and specifically the DOD.

While the United States is plagued with short-term thinking, China is aggressively looking toward winning in the contested resource-competition environment. David Archibald states that China “has assessed the resources that nature has given it and is getting on with the job of securing its energy future.”⁷⁸ The United States needs to develop compact nuclear reactors based on thorium, which becomes fissile fuel when processed and is accessible and abundant enough to last millennia. With the exception of the Navy and recent plans to construct five new nuclear power plants, the United States is overwhelmed with short-term thinking, which includes minimal nuclear research. At the same time, China is embracing long-term thinking and commercializing quickly thorium-burning, molten-salt technology.⁷⁹

Additionally, besides political hurdles, discussed shortly, the DOD should take into account other considerations when implementing a plan of developing and fielding compact nuclear reactors. As with any new technology, the DOD should start with demonstrations before operationalizing the new nuclear reactor technology. When operationalizing nuclear-powered aircraft, the Air Force should start with aircraft with the least chance of contact with the enemy, such as cargo and ISR platforms, before putting nuclear reactors on all types of aircraft.

Although the Air Force has already flown a nuclear reactor on a B-36 and demonstrated it can design an engine for a nuclear-powered B-47, it needs to examine nuclear reactors for modern aircraft. Since some Air Force aircraft currently are capable of supersonic speeds, future aircraft need to be designed to achieve comparable speeds, which, at least at first, may require a hybrid of nuclear and traditional technology. In addition, the Air Force should start with flying nuclear-powered aircraft over remote or unpopulated areas, such as over water, before flying over

populated areas. Likewise, as the Army already demonstrated in the 1960s and 1970s, the DOD should start by putting compact nuclear reactors on remote bases before putting them at all bases. In short, the DOD, especially the Air Force, should build its nuclear reactor program first in conservative environments to demonstrate the technology and build public trust. Then it should expand the technology to more realistic and hostile environments.

Political Hurdles

Political willpower, more than technology, is limiting the expansion of the DOD's nuclear power program. Sure, the DOD needs technological advancements for the latter part of the implementation plan, explained shortly, such as transitioning to compact fusion reactors, which currently do not exist. However, with minimal new technology and mostly just new engineering for modern aircraft and bases, the DOD could use existing, proven technology to expand its nuclear power program immediately. However, the DOD first must overcome at least two political hurdles: poor public perception regarding nuclear technology and the current law constraining nuclear-powered aircraft.

First, the DOD must change perceptions regarding nuclear technology. Based on nuclear weapons, memory of the Cold War, growing amounts of nuclear waste, and memorable nuclear accidents, some Americans fear nuclear technology and are against the development of it, regardless if it is for war or peaceful purposes. Nuclear weapons and reactors have tremendous power. Humans across the globe will always remember the horrific images of Hiroshima and Nagasaki hit with US fission bombs, as well as images after nuclear disasters. These disasters include those at Three Mile Island, Pennsylvania in 1979; Chernobyl, Ukraine in 1986; and Fukushima, Japan in 2011. The average age of the 99 US nuclear power plants is currently 36 years. The rate of construction of new power plants slowed considerably after the Three Mile

Island and Chernobyl incidents. The newest US nuclear power plant has been operating since 1996, but the United States has begun constructing five new nuclear power plants, which may be an indicator of perceptions already starting to change.⁸⁰

Using the perfect safety record of American nuclear-powered naval vessels and spacecraft, the DOD can minimize this first political hurdle and promote the safety of nuclear-powered aircraft and bases to the American public. Like with nuclear weapons, the key to safety of nuclear-powered aircraft and bases is maintaining several layers of redundant safety mechanisms. Bases already have security measures in place, such as perimeter fences, controlled access, and dedicated security forces personnel. In addition, compact nuclear reactors are safer than the large reactors of the past disasters. Finally, future compact reactors based on thorium-burning, molten-salt technology will be safer, since the fuel itself does the circulating, unlike current reactors where the coolant, usually water, circulates. Practically, this change in what circulates makes shutting down the reactor easier if an emergency occurs.⁸¹

Two contributing factors to the poor public perception regarding nuclear technology are the fine line between using nuclear technology for peaceful and war purposes and the difficulty in understanding and predicting intentions. For example, even though Iran continues to assert it wants to develop a nuclear-power program for peaceful, energy-infrastructure purposes, the United States and Israel continue to assume Iran's intentions are to develop nuclear weapons. The difference between using nuclear technology for peaceful and war purposes is the degree plant operators have to process or enhance the fissile material using centrifuges. Culminating years of discussions and diplomacy over the issue, Iran in April 2015 agreed to an increased number of inspections and a decreased number of operating centrifuges and its stockpile of low-enriched uranium. In return, the United States promised fewer economic sanctions. President

Obama stated that the deal “cuts off every pathway” for Iran to develop a nuclear weapon and that “if Iran cheats, the world will know it.”⁸²

As far as the second political hurdle, the DOD must consider the law regarding nuclear-powered aircraft. Although current law does not explicitly exclude nuclear-powered aircraft, mostly for safety and security reasons, the DOD should convince Congress to change US law to make their existence and usage implicitly legal, just like it did in the past for nuclear-powered naval vessels. Additionally, the United States would need to lobby to update international law. Lt Col Brian Grelk, in his ACSC research, examined international and US nuclear law and principles, especially focusing on safety, security, compensation, and compliance principles. He points out that the law does not mandate zero risk, but the DOD should consider operational constraints on nuclear-powered aircraft to ensure the security and safety of people and the environment.⁸³

Implementation Step 1 (2015-2020): Increase DOD Nuclear Technology Research

In order to transition away from fossil fuels and instead increase its nuclear power program, the DOD must start immediately. As an interim step toward fossil-fuel independence, the DOD, and really the United States as a whole, should continue diversifying its energy sources. The transition away from fossil fuels will take decades, but the DOD could manage it with four implementation steps: increase DOD nuclear technology research, expand current compact nuclear reactors used on naval vessels for other uses, transition from uranium-based reactors to thorium-based reactors, and use compact fusion reactors.

First, the DOD must start today by investing more in the research and development of nuclear reactor technology, especially compact nuclear reactors. The DOD has a long and successful history of developing nuclear technology, from the Army’s past operational usage of

compact nuclear reactors to power remote bases to the Air Force's successful demonstrations of nuclear reactor technology for aircraft. Leveraging past research as well as current technology in the Navy, the DOD is positioned already to expand its nuclear power program.

Additionally for this first step, the DOD should increase its collaboration with both the DOE and industry. The DOD already has strong relationships with both, but should now focus the collaboration on compact nuclear reactors and for nuclear-power aircraft and bases. The strong relationship with the DOE and its predecessor organization, the AEC, goes all the way back to the Manhattan Project. Today, the Air Force sends people and works with DOE labs at Sandia, Oakridge, Argonne, Lawrence Livermore, and Los Alamos. The Air Force and Army should also implement nuclear-focused exchange assignments with the Navy. Furthermore, the DOD should collaborate more with industry. For example, Lockheed Martin is looking for government sponsorship for its compact nuclear reactor research.

Specifically, the DOD should reform its nuclear enterprise and focus its research for the next six years in several areas. All services should work together and constantly share research and development results, but each service can take the lead in certain areas. The Army should take the lead, as it did from 1952 to 1979, in developing compact nuclear reactors for bases. The Navy, which already has a successful program, can expand that program and concentrate on using compact nuclear reactors and desalination technology on barges to turn seawater into potable drinking water and hydrogen fuel for transportation needs. The Navy should also continue its research into advancing the current VIRGINIA-class reactor. Finally, the Air Force should take the lead on developing nuclear-powered aircraft. It should take the results of its past research, while considering progress with lightweight shielding, and develop engines for implementation onto modern aircraft. Furthermore, now is the time to increase research on

thorium-based nuclear reactors and partner with industry to develop compact fusion reactors for steps three and four, respectively. In short, for the next six years, the DOD should strengthen its partnerships with both the DOE and industry and focus its nuclear technology research on compact nuclear reactors.

Step 2 (2020-2030): Compact Uranium-Burning, Water-Cooled Fission Reactor

Second, between 2020 and 2030, the DOD should replicate the already-proven, VIRGINIA-class reactor from the Navy and engineer it for bases, barges, and aircraft. The Navy currently fuels this fission reactor with uranium and cools it with pressurized water. In the next decade, the Army should demonstrate and implement such a reactor on a remote US base, paving the way for eventual implementation of nuclear-powered bases DOD-wide. The Navy should demonstrate and implement such a reactor paired with desalination technology on a barge for purposes of potable water and hydrogen fuel. Finally, the Air Force should demonstrate such a reactor on a cargo aircraft overwater, paving the way for eventual implementation for other aircraft and for flying over land. In short, leveraging existing technology is the quickest and easiest nuclear solution, and the DOD should plan for technology demonstrations on an aircraft, on a barge, and on a remote base by 2020.

Step 3 (2030-2040): Compact Fission Reactor Using Thorium

Third, between 2030 and 2040, the DOD should modify the VIRGINIA-class reactor into a compact fission reactor using processed thorium instead of uranium for fuel and molten-salt instead of water as the coolant. Thorium molten-salt reactors are better than current uranium-burning, light-water reactors for at least three reasons. First, they are safer, as the fuel itself does the circulating instead of the coolant, which is crucial for shutting down during emergencies. Second, thorium is more abundant than uranium and plutonium, and the supply of thorium could

last for millennia. Third, using thorium actually helps solve the nuclear waste problem. Thorium is lighter than uranium and cannot be fissile fuel all by itself. However, when combined with certain isotopes of radioactive nuclear waste, the thorium transmutes into fissile uranium. Therefore, the US could reprocess its nuclear waste, which other countries currently do, for useful purposes instead of letting it cumulate into an unmanageable problem.⁸⁴ Once developed and proven, the DOD should then use the compact thorium molten-salt reactor for bases, barges, and aircraft, leveraging lessons learned from the previous two steps.

Step 4 (2040-2050): Compact Fusion Reactor

Fourth, as a solution for 2040 and beyond, the DOD should use compact fusion reactors to power aircraft, naval vessels, and bases. Like fission, fusion reactors have options for fuel. These options include hydrogen, deuterium, lithium, and helium-3. The first three are abundant on the earth, and the fourth is abundant on the moon. Fusion is more efficient than fission, and compact fusion reactors from industry should exist by 2040, as a result of developments in plasma physics. Although Lockheed Martin claims they will have an operational compact nuclear fusion reactor in 10 years with government sponsorship, 25 years is probably more realistic. Lockheed Martin plans to use deuterium or lithium as the fuel. They predict they will have a prototype in five years, that their reactor can fit “on the back of a truck,” and that the reactor will have an output of 100 megawatts,⁸⁵ which is enough to power a small city and to serve DOD needs.

Conclusion

The DOD must prepare for the future when the operational environment will be highly contested and the cost of and the requirements for energy will be even greater than today. In fact, the DOD is currently planning for the problem of being able to project power in a highly

contested environment. It must be able to do so without burning fossil fuels, which is bad for the environment. Additionally, fossil fuels may run out in as short of time as 100 years. The most efficient energy-producing method is nuclear power. Therefore, the DOD should transition away from fossil fuels and transition toward additional nuclear power. It can do this by leveraging decades of past research of its own and collaborating with the DOE.

Political willpower, more than technology, is limiting the DOD's nuclear-power program. Most nuclear reactors operating around the world today are large and consist of outdated fission technology, mostly as a result of unadaptable industrial inertia going all the way back to the American Manhattan Project of the 1940s. However, compact fission reactors exist today that are safer and easier to put into place worldwide. Such reactors have propelled naval vessels for sixty years. The DOD, DOE, and industry should collaborate to advance further compact fission reactors and to develop compact fusion reactors. These compact reactors could then power bases, decreasing the DOD's footprint and time needed to set up such bases. The DOD could operate them on barges equipped with desalination technology for converting seawater into potable water and hydrogen fuel for transportation use. Finally, they could also power aircraft, increasing loiter time and power-projection range. The applications of compact nuclear reactor technology, both inside and outside the DOD, are numerous, including even propelling spacecraft to the stars. The compact nuclear reactor is the solution for US long-term energy needs.

ENDNOTES

(All notes appear in shortened form. For full details, see the appropriate entry in the bibliography.)

1. US National Security Strategy, 16.
2. US Department of Defense Quadrennial Defense Review, iii.
3. US Energy Information Administration. Value was extrapolated from data linear trend line.
4. Wayback Machine. *Energy Units*.
5. Roberts.
6. US Energy Information Administration.
7. Hargraves, 60.
8. Kaku, 246.
9. Ibid., 244.
10. Posner.
11. Ibid.
12. US Department of Defense. *Opportunities for DOD Use of Alternative and Renewable Fuels*, iv.
13. For example, the United States publically recognized that leaded gasoline was toxic in 1971 but was not able to phase out leaded gasoline completely until 1995 [Environmental Protection Agency]. Inside the Air Force, even though jet technology first surfaced in the 1930s, the Air Force only moderately used jets in the Korean War and did not fully adopt the technology until the Vietnam War.
14. Lengyel, 10.
15. Starosta, 35.
16. Ibid., 35.
17. Hargraves, 60.
18. US Energy Information Administration.
19. Wayback Machine. *Energy Equivalents*.
20. Klare, 13.
21. Gold, 6.
22. Archibald, 9.
23. Kaku, 243.
24. US Energy Information Administration. Dollar amounts are in 2012 US dollars. Data available for other years besides 1990-2012, but author chose these years for simplicity. Data is the West Texas Intermediate (WTI) crude oil price.
25. Isidore.
26. US Department of Energy, *Annual Energy Outlook 2014 with Projections to 2040*, CP-3. Data is the West Texas Intermediate (WTI) crude oil price.
27. Archibald, 137.
28. Ibid., 8.
29. Palley, 9. Many other sources exist.
30. US Department of Defense Quadrennial Defense Review, iv.
31. Bender.
32. US National Security Strategy, 16.
33. Goldfein, memorandum for record.

-
34. Foster, 53.
 35. US National Security Strategy, 16.
 36. Palley, 19.
 37. Kaku, 244.
 38. Ibid., 247-248.
 39. Ibid., 247.
 40. Posner.
 41. Ibid.
 42. President, "Remarks by President Obama at Hankuk University."
 43. Shane.
 44. Kaku, 272. Humans cannot convert water into energy via fusion currently. Kaku based this number on the calculated energy output of stellar fusion.
 45. Martin, 2.
 46. Palley, 19.
 47. Posner.
 48. International Atomic Energy Agency.
 49. Kaku, 254. Kaku stated in 2011 that the United States has no plans to construct new nuclear power plants. Since 2011, the United States has developed plans.
 50. International Atomic Energy Agency.
 51. US Department of Defense. *The United States Naval Nuclear Propulsion Program*, 1.
 52. International Atomic Energy Agency.
 53. Blanke et al.
 54. The eight countries are the United States, Russia, France, China, the United Kingdom, India, Pakistan, and North Korea.
 55. Pfeffer and Macon.
 56. US Department of Defense. *The United States Naval Nuclear Propulsion Program*, 1.
 57. Ibid.
 58. Brookings Institution, *Converted B-36 Bomber*, 2.
 59. Ibid.
 60. Cortright.
 61. Palley, 17.
 62. International Atomic Energy Agency.
 63. Hargraves, 23.
 64. Archibald, 156-157.
 65. Kaku, 255.
 66. Palley, 155-156.
 67. US Department of Defense. *The United States Naval Nuclear Propulsion Program*, 19,29-30.
 68. Ibid., 3,29-31,34.
 69. Ibid., 3.
 70. Cortright.
 71. US Air Force. *B-2 Sprit Fact Sheet*.
 72. Grelk, 1.
 73. Pfeffer and Macon.
 74. Dyson.
 75. Orth, i.

-
76. Archibald, 156,158.
 77. Shalal.
 78. Archibald, 161.
 79. Ibid., 159.
 80. International Atomic Energy Agency.
 81. Archibald, 158.
 82. Gordon and Sanger.
 83. Grelk, 7-15.
 84. Archibald, 156-161.
 85. Norris.



Bibliography

- Archibald, David. *Twilight of Abundance: Why Life in the 21st Century will be Nasty, Brutish, and Short*. Washington, DC: Regnery Publishing, 2014.
- Azzano, Col Christopher P. "Going for Gold: A Path Toward Petroleum-Independence in the 2030 Air Force." Research Report no. AETC-2011-0626. Maxwell AFB, AL: Air War College, 2011.
- Bender, Brian. "Navy Admiral Samuel J. Locklear Says the Biggest Security Threat in the Pacific Region is Climate Change." <http://www.wsj.com/articles/SB10001424127887323826704578356702694593938> (accessed 29 March 2015).
- Blanke, B.C., J.H. Birden, K.C. Jordan, E.L. Murphy. *Nuclear Battery-Thermocouple Type Summary Report*. Miamisburg, Ohio, 1960.
- Brookings Institution. "Converted B-36 Bomber", The US Nuclear Weapons Cost Study Project, Aug 1998. <http://www.brookings.edu/projects/archive/nucweapons/anp.aspx> (accessed 29 March 2015).
- Conner, Steven. "Warning: Oil Supplies Are Running Out Fast," *Independent*. 3 August 2009, <http://www.independent.co.uk/news/science/warning-oil-supplies-are-running-out-fast-1766585.html>.
- Cortright, Vincent. "Dream of Atomic Powered Flight." *Aviation History*, March 1995. <http://www.megazone.org/ANP/atomair.shtml> (accessed 7 April 2015).
- Dyson, George. *Project Orion: The True Story of the Atomic Spaceship*. New York, NY: Henry Holt and Co., 2002.
- Foster, Harry. "The Joint Stealth Task Force: An Operational Concept for Air-Sea Battle." *Joint Forces Quarterly* 72, 1st Quarter 2014: 47-53.
- Gold, Russell. *The Boom: How Fracking Ignited the American Energy Revolution and Changed the World*. New York, NY: Simon & Schuster, 2014.
- Goldfein, Lt Gen David, director of joint staff, US Air Force. Memorandum for record, 8 January 2015.
- Goodstein, David L. *Out of Gas*. New York, NY: W.W. Norton, 2004.
- Gordon, Michael R. and David E. Sanger. "Iran Agrees to Detailed Nuclear Outline, First Step Toward a Wider Deal." *Nytimes.com*, 2 April 2015. http://www.nytimes.com/2015/04/03/world/middleeast/iran-nuclear-talks.html?_r=0 (accessed 8 April 2015).

- Grelk, Brian J. *Nuclear-Powered Aircraft: Potential Air Force's Alternative Fuel Persistence and Reach Platform or Crazy Idea?* Research Report. Maxwell Air Force Base, AL: Air Command and Staff College, 2009.
- Hargraves, Robert. *Thorium: Energy Cheaper Than Coal*. Hanover, NH: Robert Hargraves, 2012.
- Hughes, Gordon. *The Performance of Wind Farms in the United Kingdom and Denmark*. London: Renewable Energy Foundation, 2012.
- International Atomic Energy Agency. Various future predictions. <https://www.iaea.org> (accessed 29 March 2015).
- Isidore, Chris. "89 Straight Days of Lower Gas Prices." <http://money.cnn.com/2014/12/23/news/economy/lower-gas-price-streak> (accessed 29 March 2015).
- Kaku, Michio. *Physics of the Future: How Science Will Shape Human Destiny and Our Daily Lives by the Year 2100*. New York, NY: Anchor Books, 2011.
- Klare, Michael T. *Rising Powers, Shrinking Planet: The New Geopolitics of Energy*. New York, NY: Holt Paperbacks, 2008.
- Lengyel, Col Gergory J. *Department of Defense Energy Strategy: Teaching an Old Dog New Tricks*. Foreign Policy Study. Washington, DC: The Brookings Institute, Aug 2007.
- Martin, Richard. *Super Fuel: Thorium, the Green Energy Source for the Future*. New York, NY: Palgrave Macmillan, 2012.
- Norris, Guy. "Skunk Works Reveals Compact Fusion Reactor Details," *Aviationweek.com*. 15 October 2014, <http://aviationweek.com/technology/skunk-works-reveals-compact-fusion-reactor-details> (accessed 11 November 2014).
- Orth, Charles D. *VISTA – A Vehicle for Interplanetary Space Transport Application Powered by Inertial Confinement Fusion*. University of California: Department of Energy, October 2003.
- Palley, Reese. *The Answer: Why Only Inherently Safe, Mini Nuclear Power Plants Can Save Our World*. New York: The Quantuck Lane Press, 2011.
- Pfeffer, Robert A. and William A. Macon, Jr. "Nuclear Power: An Option for the Army's Future," *Almc.army.mil*. Sep 2001, <http://www.almc.army.mil/alog/issues/SepOct01/MS684.htm> (accessed 7 April 2014).
- Posner, Rachel. "DoD Releases Comprehensive Energy Policy," *Energy.defense.gov*. 16 April 2014, <http://energy.defense.gov/Blog/tabid/2569/Article/8676/dod-releases-comprehensive-energy-policy.aspx>.

- President. "Remarks by President Obama at Hankuk University," Seoul, Republic of Korea: Hankuk University, 12 Mar 2012. <https://www.whitehouse.gov/the-press-office/2012/03/26/remarks-president-obama-hankuk-university>.
- President. "The National Security Strategy of the United States of America," Washington, DC: The White House, Feb 2015.
- Roberts, Tristan. *What is a Watt, Anyway? Understanding Energy and Power Metrics*. <http://www2.buildinggreen.com/blogs/what-watt-anyway-understanding-energy-and-power-metrics> (accessed 20 May 2015).
- Shalal, Andrea. "LOCKHEED: We Made A Huge Breakthrough In Nuclear Fusion," *Business Insider*. 15 October 2014, <http://www.businessinsider.com/andrea-shalal-lockheed-nuclear-fusion-breakthrough-2014-10> (accessed 11 November 2014).
- Shane, Leo, III. "White House Eyes Military, Vets for Solar Energy Goals," *Militarytimes.com*. 3 April 2015, <http://www.militarytimes.com/story/military/benefits/education/gi-bill-ta/2015/04/03/solar-energy-vets-jobs/25239129/> (access 5 April 2015).
- Starosta, Gabe. "The Air Force's Fuel Problem." *Air Force Magazine*, July 2012, 35-38.
- US Air Force. *B-2 Spirit Fact Sheet*. Barksdale Air Force Base, 1 Apr 2005. <http://www.af.mil/AboutUs/FactSheets/Display/tabid/224/Article/104482/b-2-spirit.aspx> (accessed 7 April 2015).
- US Department of Defense. *DoD Energy Policy*. Washington, DC: Office of the Undersecretary of Defense (Acquisition, Technology, and Logistics), April 2014.
- US Department of Defense. *Opportunities for DoD Use of Alternative and Renewable Fuels*. Washington, DC: Office of the Assistant Secretary of Defense (Operational Energy Plans and Programs), July 2011.
- US Department of Defense. "Quadrennial Defense Review 2014," Washington, DC: The Pentagon, Mar 2014.
- US Department of Defense. *The United States Naval Nuclear Propulsion Program*. Lexington, KY: Department of the Navy, March 2015.
- US Energy Information Administration. "Annual Energy Outlook 2014 with Projections to 2040," Washington, DC: Department of Energy Headquarters, Apr 2014.
- US Energy Information Administration. Various future predictions. <http://eia.gov> (accessed 29 March 2015).

US Environmental Protection Agency. *Leaded Gas Phaseout*. Washington, DC, Jun 1995.
<http://yosemite.epa.gov/R10/airpage.nsf/webpage/Leaded+Gas+Phaseout> (accessed 29 March 2015).

Wayback Machine. *Energy Equivalents*. https://web.archive.org/web/20100615153419/http://nafa.org/Template.cfm?Section=Energy_Equivalents (accessed 19 May 2015).

Wayback Machine. *Energy Units*. <http://web.archive.org/web/20080310073316/http://members.aol.com/BearFlag45/Biology1A/Reviews/energy.html> (accessed 20 May 2015).

